EMS504U - HEAT and MASS TRANSFER

Combined Convection (Natural/Free or Forced) and Radiation Heat Transfer from a Horizontal Cylinder

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Introduction and Background Theory

In this lab, we were asked to investigate combined convection (Natural/Free or Forced) and Radiation Heat Transfer from a Horizontal Cylinder**.** Heat transfer deals with systems that are not in thermal equilibrium and can be divided into 3 different types (Conduction, Convection and Radiation) and during practical situations all three types of heat transfer may be present, but one may be more dominant than the others and we investigated heat transfer from a heated horizontal cylinder cooled by air. This was achieved through 2 experimental methods:

1. Combined natural/free convection and radiation
2. Combined forced convection and radiation

We were also asked to compare the numerical experimental results gathered during the lab with theoretical results from the literature and the success of the trends compared to the theory. There are 2 types of heat transfer where the first is steady heat flow where temperatures can vary with space only and the second, is transient heat flow, where the tempreture is a function of both time and space. During heat transfer, the 1st and 2nd law of thermodynamics must be obeyed. The 1st law of thermodynamics energy cannot be created or destroyed, but can be transferred from one form to another. (Encyclopedia Britannica, 2023) The 1st law can be written as the equation below:

$$\Delta U = Q - W \tag{1.1}$$

Where, U is the is internal energy, Q is the heat added to the system and W is the work done by the system. The 2nd law of thermodynamics states the state of entropy of an isolated system will always increase over time. This means that heat only moves from a reservoir of higher temperature to lower temperature in a closed system. (Encyclopedia Britannica, 2023) This can written as shown in the equation below, where S is the entropy, Q is heat transfer, and T is temperature:

$$\Delta S = \frac{Q}{T} \tag{1.2}$$

The 3 main types of heat transfer, which are conduction, convection and radiation can occur alone however most engineering applications combine 2 or all 3 modes of heat transfer. Conduction occurs when there is a temperature gradient present as it transfer molecules from areas of higher temperature to areas of lower temperature and only occurs in solids and stationary fluids (UWSP. 2023. Unit 2 - Section B). The equation below shows how one dimensional conduction heat rate equation:

$$Q_{cond} = -kA\frac{dT}{dx} \tag{1.3}$$

Where, k is the thermal conductivity of the material, A is the cross sectional area, T is the temperature and x is the length. However, conduction can be ignored during this lab. Convection occurs between a solid and a fluid in motion by a bulk movement of the fluid which transports the energy. Convection heat rate can be solved by using the equation below:

$$Q_{conv} = h_{conv}\, A\, (T_2 - T_1) \tag{1.4}$$

Where, Q is the convection heat rate, h_{conv} is the heat transfer coefficient, A is the cross sectional area, with T being the temperatures. h_{conv} can be solved using the formula below as it is natural convection from a cylinder

$$h_{conv} = 1.32\left(\frac{T_2 - T_1}{D}\right)^{0.25} \tag{1.5}$$

Where D is the diameter of the cylinder. Radiation is the final type of heat transfer and it occurs though electromagnetic waves. There is no medium required for heat transfer and each body absorbs thermal radiation from all bodies at the same rate at which it emits energy in equilibrium. The heat rate caused by radiation can be solved using one of the equation below.

$$Q_{rad} = \epsilon\, A\, \sigma\, (T_2^4 - T_1^4) = h_{rad}\, A\, (T_2 - T_1) \tag{1.6}$$

However, to find the radiation component of the overall heat transfer coefficient we need to use the formula below:

$$h_{rad} = \epsilon\, F\, \sigma \frac{T_2^4 - T_1^4}{T_2 - T_1} \quad (1.7)$$

Where Q is the convection heat rate, ϵ is the emissivity coefficient of the object surface, A is the cross sectional area, σ is the Stephan-Boltzmann constant, which is equal to 5.67 x10^{-8} W/mK, T is the temperature and F is the view factor which is the proportion of adiation that leaves one surface to strike another surface. The reason why we need to equate the radiation and convection heat rate equations to find h is because the adiation heat rate equation doesn't contain the h term. Using h_{conv} and h_{rad}, we can work out the total theoretical heat transfer coefficient from the cylinder shown below:

$$h_{total\ theoetical} = h_{conv} + h_{rad} \quad (1.8)$$

However, total experimental heat transfer coefficient can be worked out using the equation below

$$h_{total\ expeimental} = \frac{Q_{input}}{A(T_2 - T_1)} \quad (1.9)$$

In the second experiment, we were asked to investigate the effect of forced convection on the heat transfer from a cylinder at varying air velocities. the heat lost due to forced convection could be solved using the equations below:

$$Q_{f conv} = h_{\ f conv}\, A\, (T_2 - T_1) \quad (1.10)$$

Where $h_{\ f conv}$ is the Overall heat transfer coefficient due to forced natural convection and for the radiant component, it can be solved using the equation below:

$$Q_{frad} = h_{frad}\, A\, (T_2 - T_1) \quad (1.11)$$

Using Q_{fconv} and Q_{frad}, we can work out the total theoretical heat transfer coefficient from the cylinder shown below:

$$Q_{total} = Q_{fconv} + Q_{frad} \quad (1.12)$$

In addition, from a nondimensional relationship, forced convection coefficient can be determined for particular geometric configurations. This can be done by

$$h_f = \frac{k}{D} Nu \quad (1.13)$$

Where, Nu is the Nusselt number, which is a non-dimensionless number. Its the ratio of convective to conductive heat transfer across a boundary. It can solved using the equation below:

$$\text{Nu} = 0.3 + \frac{0.62 \times Re^{0.5} \times Pr^{0.33}}{(1+(\frac{0.4}{Pr})^{0.66})^{0.25}} \times \left(1 + \left(\frac{Re}{282000}\right)^{0.5}\right) \quad (1.14)$$

Where, the Reynolds number, Re can be solved below:

$$\text{Re} = \frac{U_e D}{v} = \frac{1.22\ U_a D}{v} \quad (1.15)$$

Apparatus and Procedure

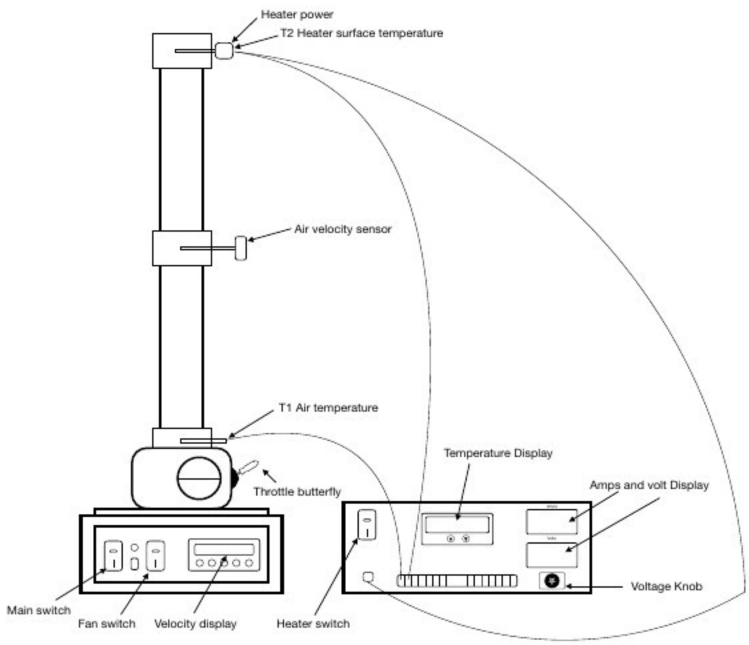


Figure 1. 2D Schematic diagram of Apparatus

Figure 1 shows how the components are linked together. The main components are heater power, the air velocity sensor, throttle butterfly, velocity display, and the main switch. The heater power provides the heat needed to heat the air. The throttle butterfly allows the velocity of the flow of the air to be changed. The velocity display displays the velocity in addition to having the main power switch and the fan switch. The temperature display, displays both T1 and T2, inaddition to showing the Amps and Voltage with a knob to control the voltage.

Procedure

Experiment 1:

1. We set the voltage to 52 V.
2. To allow air circulation through the duct, we opened the throttle butterfly.
3. We then waited for T2 to reach a steady state temperature.
4. We recorded T1, T2, voltage and current.
5. We set the voltage to 101 V.
6. We waited for T2 to reach a steady state temperature then repeated step 4
7. We set the voltage to 151 V.
8. We waited for T2 to reach a steady state temperature then step 4 was repeated.

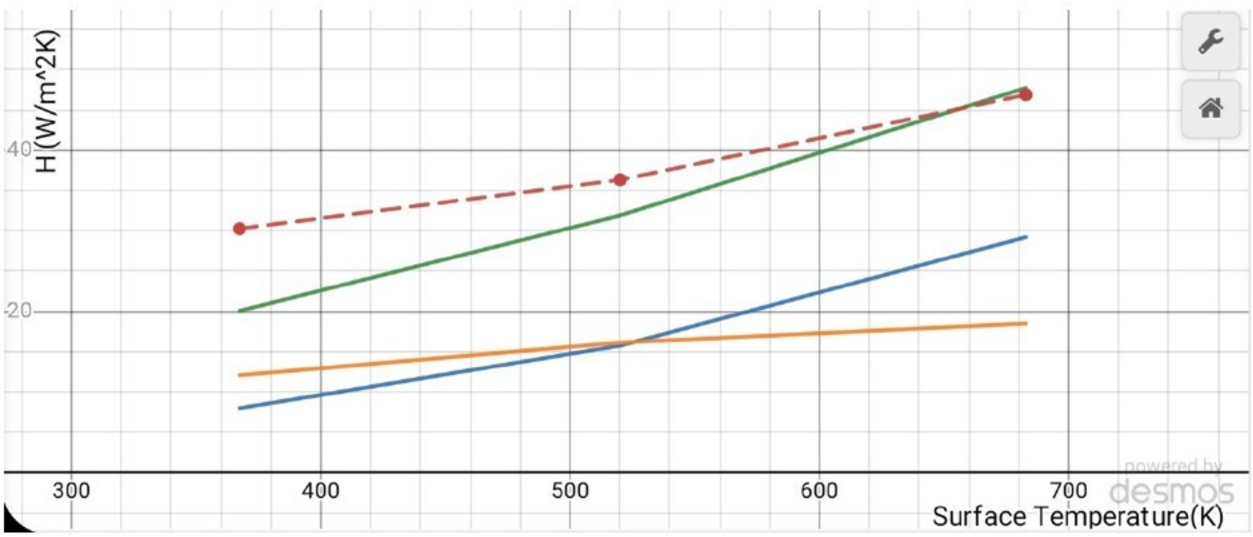
Experiment 2:

1. Keeping the voltage at 151 V, we turned on the fan.
2. We adjusted the air velocity to 0.98 m/s using the throttle butterfly.
3. We waited for T2 to reach a steady state temperature.
4. We recorded T1, T2, voltage, current and the air velocity.
5. We adjusted the air velocity to 3.00 m/s
6. We waited for T2 to reach a steady state temperature then repeated step 4.
7. We adjusted the air velocity to 5.00 m/s
8. We waited for T2 to reach a steady state temperature then repeated step 4.
9. We adjusted the air velocity to 7.00 m/s
10. We waited for T2 to reach a steady state temperature then repeated step 4.

Results

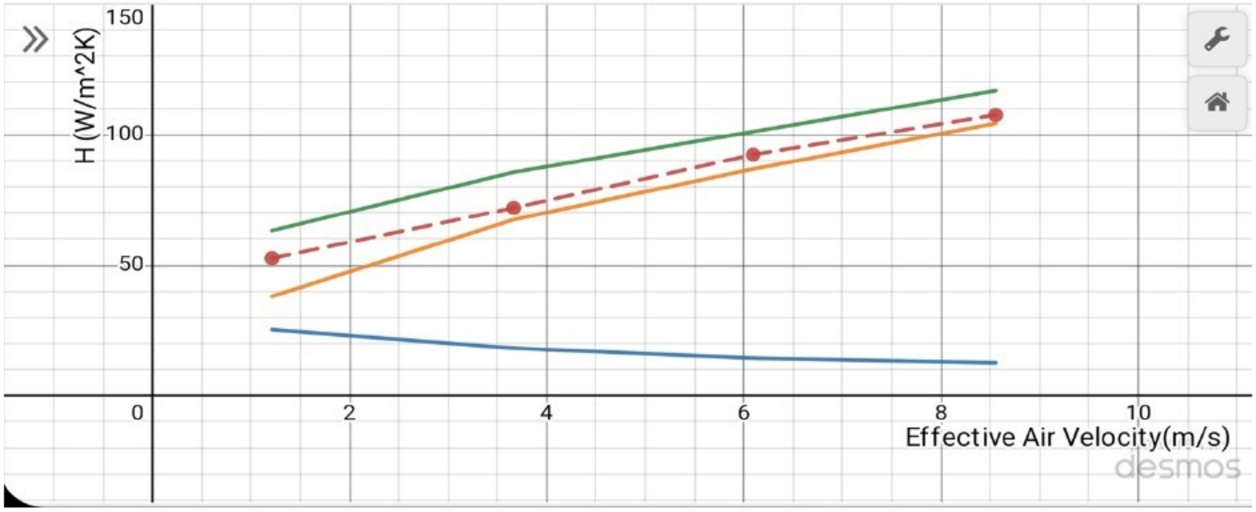
Table 1: Experiment 1					
Surface Temperature(K)	Hr (theoretical) (W/m^2K)	Hc (theoretical) (W/m^2K)	Ht(theoretical) (W/m^2K)	Ht(experimental) (W/m^2K)	% difference between Ht(theoretical) and Ht(experimental)
367.417	7.99	12.09	20.08	30.27	50.75
520.117	15.76	16.14	31.90	36.31	13.82
682.85	29.21	18.51	47.72	46.86	1.80

Table 2: Experiment 2					
Effective air velocity(m/s)	Hr (theoretical) (W/m^2K)	Hf (theoretical) (W/m^2K)	Ht (theoretical) (W/m^2K)	Ht (experimental) (W/m^2K)	% difference between Ht (theoretical) and Ht (experimental)
1.2139	25.23	37.97	63.20	52.62	16.74
3.6661	18.14	67.44	85.58	71.89	16.00
6.0939	14.31	86.81	101.12	92.32	8.70
8.5522	12.54	104.26	116.80	107.50	7.96



Graph 1. Results for experiment 1

Ht Experimental
Ht Theoretical
Hc Theoretical
Hr Theoretical



Graph 2. Results for experiment 2

- - - - - Ht Experimental
Ht Theoretical
Hc Theoretical
Hr Theoretical

Experiment 1 sample calculation:

V = 52 V
I = 0.090 A
T1 = 297.15 K
T2 = 367.417 K

$Q_{input} = V \times I = 52 \times 0.09 = 4.68$ W

$h_r = \varepsilon f \sigma \frac{Ts^4 - Ta^4}{Ts - Ta} = 0.95 \times 1 \times 5.67 \times 10^{-8} \times \frac{367.417^4 - 297.15^4}{367.417 - 297.15}$

$h_r = 7.99$ W/m^{2}K

$h_c = 1.32 \times (\frac{Ts - Ta}{D})^{0.25}$

$h_c = 1.32 \times (\frac{367.417 - 297.15}{0.01})^{0.25}$

$h_c = 12.09$ W/m^{2}K

$h_{total,theoretical} = h_r + h_c = 12.09 + 7.99 = 20.08$ W/m^{2}K

$h_{total,experimental} = \frac{Q_{input}}{A_S(Ts - Ta)} = \frac{4.68}{0.0022(367.417 - 297.15)} = 30.27$ W/m^{2}K

Experiment 2 sample calculation:

Speed = 0.995 m/s
V=150V
I = 0.264A
T_1 = 298.25 K
T_2 = 640.317 K

$Q_{input} = V \times I = 150 \times 0.264 = 39.6$ W

$h_r = \varepsilon f \sigma \frac{Ts^4 - Ta^4}{Ts - Ta} = 0.95 \times 1 \times 5.67 \times 10^{-8} \times \frac{640.317^4 - 298.25^4}{640.317 - 298.25}$

h_r = 25.23 W/m²K

u_e= 0.995 × 1.22 = 1.2139 m/s

<u>Discussion</u>
Temperature measurements are made along the cylinder and in the surrounding fluid as part of experimental research on convective heat transfer from a horizontal cylinder. Higher Reynolds numbers and temperature differences are often associated with enhanced heat transfer, according to the results. It is difficult to detect radiation heat transfer experimentally and requires accurate temperature control and measurement.

In the first experiment's results, we discovered that as the surface temperature increased, the heat transfer coefficients increased too. The trend of the predictions solved from the calculated data matches this aswell. We also see that the percentage difference deceases from 50% to 1.8%, as the surface temperature is increased, meaning the accuracy of the theoretical values increases as the surface temperature is increased. However, we can see the theoretical and experimental values for heat transfer coefficients intersect in graph 1. This could mean that the percentage difference could increase at a higher voltage, meaning a decrease in accuracy. This could be due to errors during the lab, assumptions, and limitations to the theory. The manufacture's manual supplied the method on calculating the heat transfer coefficients however assumptions had to be made with the experimental calculations which could be a reason for the change in accuracy.

In the second experiment, we were observing forced convection, and graph 2 showed us that as the value of effective ai velocity increased the values of our heat transfer coefficients increased proportionally, however, we saw that the radiation component of the theoretical heat transfer (Hr) decreased as air velocity increased. The cause of the increase in the values of heat transfer coefficients could be due to air being propelled assisting the rate of heat transfer due to the fan being tuned on. We can also see the percentage difference between the theoretical heat transfer coefficient and experimental heat transfer coefficient decrease from 16.84% to 7.96% as the air velocity increased.

Additional explanations for differences between theoretical and experimental findings in the investigation of heat transport from a horizontal cylinder by coupled convection and radiation include Simplifying Assumptions, Boundary Layer Effects, Surface and material Properties, the Experimental Conditions, Heat Losses and transient effects. Theoretical models may rely on oversimplified assumptions that don't fully capture real-world complexities, such as calculating the properties of air at an "average temperature" even though the temperature varied throughout the cylinder. We also assumed that velocity was constant throughout experiment 2 even though it was fluctuating with time. Inaccuracies in surface properties, like emissivity, could affect the radiation heat transfer predictions in the calculations. Variations between actual conditions and theoretical assumptions can cause disparities. We assumed that temperature, pressure, and humidity stayed constant, however, due to students' breathing and wind from outside (as the windows were open) they could vary. In addition, neglecting or inaccurately estimating heat losses to surroundings affected our results and unsteady behaviors that are challenging to model can lead to differences. Moreover, as a group we had to record the V, I, T1, and T2 when we subjectively decided that the temperature was changing slowly enough to assume it is constant, this means that the temperature didn't reach its maximum, instead we arbitrarily chose a temperature that was somewhat close to the maximum.

Conclusion

In conclusion, the lab experiments on combined convection and radiation heat transfer from a horizontal cylinder provided detailed information and results about the behavior of these heat transfer systems. The theory predicts that as the Reynold's number increases, convective heat transfer rises due to enhanced flow turbulence and as the temperature of the cylinder increases, radiation heat transfer also increases, proportional to the fourth power of absolute temperature. The results from the experiment reveal that heat transfer increases with higher Reynold's numbers and temperature differences. Despite the slight discrepancies between theoretical predictions and the experimental results, it can be said that the results are generally consistent with theoretical predictions, therefore validating their accuracy. Overall, the experiment was successful in achieving its objectives. These results will be helpful in the future when designing more effective heat transfer systems. If given the opportunity to use more time to do the experiment, this would have certainly helped us. If given more time we would have taken more trials so that our results are more precise but most importantly we would wait until the temperature literally reached it's maximum (when it can't increase anymore). Because of time constraints we had to take a temperature as a "maximum" if it was changing slowly (i.e: not at it's maximum).

Appendix

Raw data

Measuring device	Least count
Thermocouple (deg C)	0.1
Voltmeter (V)	1
Ammeter (A)	0.001
Anemometer (m/s)	0.01

Experiment 1								
Sample Number	Voltage (V)	Current (I)	T1 (deg C) A	T1 (deg C) B	T1 (deg C) C	T2 (deg C) A	T2 (deg C) B	T2 (deg C) C
1	52	0.090	24.1	24.0	23.9	94.3	94.1	94.4
2	101	0.177	23.3	23.2	23.1	247.1	247.0	246.8
3	151	0.264	23.0	23.1	22.9	409.9	409.7	409.5

Experiment 2										
Sample Number	Velocity A (m/s)	Velocity B (m/s)	Voltage (V)	Current (A)	T1 (deg C) A	T1 (deg C) B	T1 (deg C) C	T2 (deg C) A	T2 (deg C) B	T1 (deg C) B
1	0.98	1.01	150	0.264	25.0	25.1	25.2	367.2	367.3	367.0
2	3	3.01	151	0.267	25.0	25.1	25.0	280.3	280.2	280.3
3	5	4.99	151	0.266	24.8	24.9	25.0	222.5	222.7	222.8
4	7	7.02	150	0.265	24.1	24.3	24.4	192.3	192.4	192.2

Linear interpolation from Appendix A - Useful Data:

$T_{average} = \frac{298.25+640.317}{2} = 469.3$ K

$\nu = 3.237 \times 10^{-5}$ m²/s

k = 0.0384 W/m·K

Pr = 0.68

$Re = \frac{U_e D}{\nu} = \frac{1.2139\times0.01}{3.237\times10^{-5}} = 375$

$$Nu = 0.3 + \frac{0.62\times Re^{0.5}\times Pr^{0.33}}{(1+(\frac{0.4}{0.68})^{0.66})^{0.25}} \times \left(1 + (\frac{375}{282000})^{0.5}\right)$$

$$Nu = 0.3 + \frac{0.62\times375^{0.5}\times0.68^{0.33}}{(1+(\frac{0.4}{0.68})^{0.66})^{0.25}} \times \left(1 + \left(\frac{375}{282000}\right)^{0.5}\right)$$

Nu = 9.889

$h_f = \frac{k}{D}Nu = \frac{0.0384}{0.01} \times 9.889$

$h_f = 37.97$ W/m^2K

$h_t = 37.97 + 25.23$

$h_t = 63.20$ W/m^{2}K

$$h_{total,experimental} = \frac{Q_{input}}{As(Ts-Ta)} = \frac{39.6}{0.0022(640.317-298.25)}$$

$h_{total,experimental} = 52.62$ W/m^{2}K

Refences

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